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Abstract. The Carrier Strike Group (CSG) and the Expeditionary Strike Group (ESG) are two common types of US Naval units consisting of multiple ships traveling as a group. All vessels within the CSG/ESG transmit and receive data via satellite, even when those vessels are within radio frequency line of sight (RFLOS). Within the CSG/ESG, satellite communications (SATCOM) are clearly necessary for vessels well forward of the main body, but could be augmented by RFLOS wireless communications for some members of the CSG/ESG. The goal of this research is to identify software technology that minimizes the barriers to employing affordable, commercially available technology (i.e., 802.11x) for ship-to-ship communications at sea. Some of the existing barriers to 802.11x communications at sea result from communication protocols that do not support the varying topologies or human network intervention one would expect to encounter within the CSG/ESG. This paper advances the concept for a predictive routing protocol that proactively addresses the topological and human issues unique to the DANN. Proactive routing will re-route the transmissions prior to interruptions, thus preventing interruption of open communication sessions.

1 CSG/ESG Communications Issues

Currently, passing data from ship-to-ship requires four separate transmissions [1]. Delays associated with signal propagation over long distances, communications protocols, network prioritization, dropped packets and other overhead issues can produce excessive delays and are often inadequate for VTC or VOIP sessions. The challenges and risks associated with some ship-to-ship data communications can be mitigated with predictive routing that eliminates the requirements for SATCOM and associated processing by the remote network operations center (NOC). The challenge of establishing and maintaining RFLOS communications at sea, with an acceptable quality of service, is rather unique. This research uses the Washington State Ferries (WSF) Wireless Internet Project as a baseline and advances that work to address a fully ad-hoc mobile network at sea. WSF research demonstrated the feasibility of pushing 802.11a up to 20 miles over water, identifying 802.11a as the baseline backhaul evaluated for the DANN [2].

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1.1 Problem Modeling

Nautical communication requirements are modeled as a time-dependent graph where each vertex represents a vessel within the CSG/ESG, and each arc represents a communications link. Some of the unique challenges facing the DANN are summarized below.

1.2 Topological Challenges

Vertices move out of range:

- Vessel may move out of range due to course, speed, currents and wind, or to avoid obstacles and localized weather patterns. This could sever a link between vertices or disconnect the entire network.
- Vessels may move out of range in response to direction from the CSG/ESG commander.
- The NPRP will predict when the arc between two vertices will break connectivity, calculate course and speed data needed for vessels to maintain connectivity and find an alternative route for use in case repositioning the vessels is not possible.

Localized Weather Patterns:

- Localized weather patterns and sea states on or near the arc linking two vertices may indicate that more complex routing would provide a higher quality of service.
- The NPRP will calculate the best route around localized weather patterns. If an alternate route does not exist, the NPRP will calculate course and speed data needed for vessels to establish an alternate route.

RF Shadowing:

- Vertices in direct communication with each other may experience a break in signal if both nodes pass on either side of a obstacle, such as an island. This obstacle can cast an RF shadow and block the signal from reaching the vertices.
- Vertices in direct communication with each other may experience a break in signal if a vessel without the ability to relay the wireless traffic passes between the two vertices. The vessel would essentially cast an RF shadow and block the signal.
- Obstacles are modeled as circular regions with a radius 1.10 times the physical radius. The additional ten percent provides an extra measure of security when calculating the time from the arc to the obstruction.
- The NPRP will predict when an obstacle will sever an arc, and determine an alternate route. If an alternate route does not exist, the NRPR will calculate course and speed data needed for vessels to establish an alternate route.

1.3 Human Intervention

DANN performance issues arising from vertices specified "out of service" due to human intervention are summarized below.

- Vessel is in emission control (EMCON) status that prohibits RF communications.
- Vessel is in maintenance status and some communications systems may be shut down for service.
- Vessel is designated "no-relay" by the CBG/ESG Commander to provide additional bandwidth for higher priority communications.
- Vessel is involved in a drill that requires the discontinuation of power to the DANN system.
- If any of these states exist, the NPRP will calculate an alternative route and, if necessary, calculate course and speed corrections for vessels to move them to locations to maintain connectivity.

2 Adaptive and Non-adaptive Protocols

Most mobile ad-hoc network routing protocols are reactive in nature. These protocols are also called "adaptive" because they change routing decisions "on-the-fly" to compensate for network traffic and topology. Adaptive routers receive information from other routers and use this information to adapt routes to the traffic and topology snapshot. An example of such a protocol is the Ad-Hoc On Demand Distance Vector (AODV) [3]. This and other reactive protocols capture variables such as signal strength, signal-to-noise ratio, and number of hops as input to routing algorithms. Data capture of these variables occurs in real-time or near real-time, causing the protocol to re-calculate the optimal routes. Non-adaptive routing protocols, sometimes called static routing protocols, generally do not base routing decisions on measurements, traffic or topology. Non-adaptive routing protocols calculate the route in advance and download the data to the router prior to the router coming on-line. Because static routing protocols are more likely to address fixed topologies, they can be more predictive in nature than adaptive protocols. The predictive nature of the NPRP should assist in maintaining network connectivity. This protocol anticipates and prevents degradations in quality of service (QOS) before they occur. For example, at distances of 20 nautical miles vessel maneuverability, i.e., the ability of a vertex to move to a new location to re-establish connectivity, is relatively slow. Once a vertex loses connectivity, it may take an unacceptable period of time to re-establish RFLOS communications. In anticipation of this state, NPRP has the ability to proactively move a vertex to a new location as it senses an impending break in communications. The system can also provide a vessel (or vessels) with course and speed to re-establish communications within the DANN after a break has occurred. The development and employment of a Nautical Predictive Routing Protocol would compensate for the unique topological and human issues surrounding the DANN. Essentially, NPRP is a hybrid of adaptive and non-adaptive protocol features, and might be called an "adaptive-static" protocol.

3 NPRP Approach

NPRP requires data from the CBG/ESG as a whole, and from each vessel in the group. The essential data available to NPRP is as follows: Each vessel broadcasts unique data to shore facilities via SATCOM. The data includes:

– position in latitude and longitude
– course in degrees
– speed in nautical miles per hour

Additionally, each vessel publishes a plan of the day that often includes planned drills, system maintenance and other activities that would generate an "out of service" state for that vertex. Other data available from the CBG/ESG includes maps showing locations of fixed obstacles and weather information identifying both regional and localized weather patterns. A localized pattern will generally display as a geographic center of activity with an effective radius and a displacement vector.

3.1 DANN Routing Metrics

Each vertex routes the signal based upon information calculated by the DANN application. Each vertex also has full-duplex capability, since transmission is achieved via an amplified sector antenna (eight to fifteen degrees on the main lobe) and reception is via an omnidirectional high-gain antenna. With this infrastructure, each vertex can transmit and receive simultaneously, eliminating the bandwidth degradation normally associated with multi-hop routing. Since the vessels communicate their position, course and speed, each router knows the distance to each vertex, calculated via the Haversine Formula [4]. Standard Great Circle calculations typically apply to distances greater than those found in the CBG/ESG. For very long distances, such as from New York to Los Angeles, an arc more accurately describes the distance. For long distances, spherical trigonometry follows the Law of Cosines:

$$cos(c) = cos(a)cos(b) + sin(a)sin(b)cos(C) \tag{1}$$

where a, b and c represent three sides of a spherical triangle and C represents the angle opposite side c. For short distances such as those found in the DANN, the Law of Cosines produces a rounding error that can be eliminated by using the Haversine Formula. Since this research addresses linear communication paths (RFLOS), the Haversine Formula provides a realistic and sufficiently accurate distance, d, between two vertices.

In the following equations, R represents the radius of the earth in kilometers.

$$d_{lon} = lon2 - lon1 \tag{2}$$

$$d_{lat} = lat2 - lat1 \tag{3}$$

$$a = (sin(dlat/2))^2 + cos(lat1)cos(lat2)sin(d_{lon}/2))^2 \tag{4}$$

$$c = 2(atan2(\sqrt{a}, \sqrt{1-a})) \quad (5)$$

$$d = R * c \quad (6)$$

In some regards, routing within the DANN takes on the appearance of a modified distance vector routing protocol, mainly because each router knows the distance to its neighboring routers. [5] Common metrics found in vector routing protocols, such as delay, are not critical for the DANN. Given two dynamic vertices connected by an arc, a few of the key considerations and metrics for the DANN are given below, expressed in terms of the arc length between the two vertices.

- Is the length of an arc 20 NM or less?
- If the arc length is 20 NM or less, is the length increasing?
- If the length of the arc is increasing, at what time will it reach 20 NM?
- What course and speed corrections should be recommended for which vertex or vertices to ensure the arc remains less than 20 NM?

Given obstacles that might break the arc i.e., land masses, other vessels or localized weather patterns:

- Will the vertices' movements cause them to pass on opposing sides of an obstacle?
- Is the obstacle large enough to cast an RF shadow to break the arc?
- If the obstacle is large enough to break the arc, at what time will this happen?
- If the obstacle is large enough to break the arc, what are the course and speed corrections for which vertex or vertices to avoid having the obstacle break the arc?

Human Intervention.

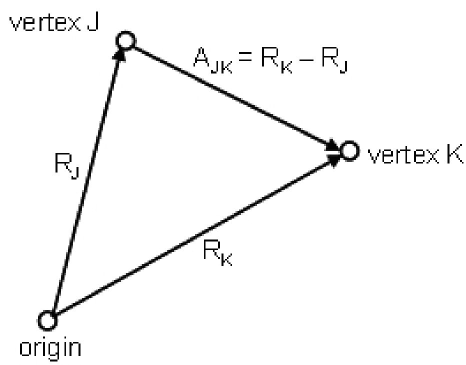
- Is a vertex scheduled to be unavailable?
- If a vertex is scheduled to be unavailable, at what time will this occur?
- If a vertex is scheduled to be unavailable, what are the course and speed corrections for which vertex or vertices to remain connected?
- If a vertex suddenly becomes unavailable, what are the course and speed corrections for which vertex or vertices to re-establish communications?

In all cases described earlier where the vessel's DANN system is out of service due to human intervention, this intervention is scheduled and generally known by other vessels within the CBG/ESG. Unexpected unavailability generally corresponds to equipment failure. In these cases, the NPRP can track the events and update the routing table to exclude those vertices that will experience out of service conditions. In cases where the out of service vertices are critical to connecting the digraph, NPRP will calculate the next-best routing path and any vertices' course and speed changes necessary to connect the digraph. If there is no next-best solution, the NPRP will identify the vertex or vertices required to connect the digraph and calculate the course/speed changes necessary to position the vertices within backhaul range.

4 The Communication Graph

The dynamic nature of the CBG/ESG subnet is accurately described by three-dimensional vector physics. [6] The formation of vessels forms a communication graph consisting of mobile vertices and arcs that exhibit the topological and human variables described earlier in this paper. Since each vertex reports current location in latitude and longitude, as well as course and speed, the NPRP will calculate when a vertex will move beyond the range of the 802.11a backhaul system. This capability is most important when the vessel moving out of range will disconnect the graph. The NPRP will also calculate a course/speed change that will keep the vessel within range and will also calculate any appropriate course/speed changes for other vertices to provide connectivity redundancy. The communication graph has n vertices numbered 1 to n. Each vertex K has a displacement vector R_K, a velocity vector V_K.

The displacement vector R_K points from an arbitrary origin to the location of the vertex. The selection of the arbitrary origin should attempt to minimize the complexity of the software required to perform the calculations relative to the DANN. Examples of convenient arbitrary origins include the center of the earth, the centroid of the geometric shape formed by the CSB/ESG, or the vertex performing the calculation.



A velocity vector relative to the arbitrary origin for vertex K is defined by

$$V_K = \frac{dR_K}{(dt)} \tag{7}$$

A displacement vector from vertex J to vertex K is

$$A_{JK} = R_K - R_J \tag{8}$$

with an arc length of

$$L_{JK} = |A_{JK}| = \sqrt{A_{JK} \cdot A_{JK}} \tag{9}$$

The derivative of the arc length is

$$\frac{dL_{JK}}{dt} = 1/2 \sqrt[-2]{A_{JK} \cdot A_{JK}} 2A_{JK} \cdot \frac{dA_{JK}}{dt} = \frac{A_{JK}}{|A_{JK}|} \cdot \frac{dA_{JK}}{dt} \tag{10}$$

Using equations (7) and (8), this becomes

$$\frac{dL_{JK}}{dt} = \frac{A_{JK}}{|A_{JK}|} \cdot (V_K - V_J) \tag{11}$$

Within the DANN, the arc length is increasing if

$$\frac{dL_{JK}}{dt} > 0 \tag{12}$$

Based upon WSF research, reliable connectivity between two vertices exists if and only if the length of the arc between the two vertices is less than less than a maximum distance M. For the 802.11x implementation discussed above, M is 20 nautical miles (NM). We can use a linear approximation for short time periods t to express the loss of connectivity condition as

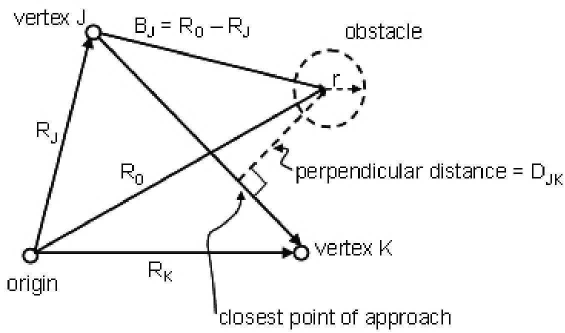
$$M = L_{JK} + \frac{dL_{JK}}{dt} t \tag{13}$$

If expression (11) shows the arc length to be increasing, equation 14 below estimates the time until vertex movement produces an arc of maximum allowable length (i.e., 20 NM) and ends reliable communication along the arc.

$$t = \frac{M - L_{JK}}{\frac{dL_{JK}}{dt}} \tag{14}$$

5 The Obstacle Problem

As an arc between two vertices moves about the ocean's surface, it may move over a land mass that can produce an RF shadow, blocking the signal from reaching the intended receiver. Additionally, other moving vessels passing between two vertices may break the link and cause a loss of communication. These situations will, at a minimum, break RF communications with one vessel, and could disconnect a larger portion of the communication graph. Land masses such as islands and localized weather patterns are depicted both on nautical charts and are visible via radar. Vessels on the ocean's surface are also identified and charted via radar. NPRP will plan for such shadowing conditions and calculate ship movements to compensate for the break in the arc, and to keep the digraph connected. To accomplish this, NPRP must measure and track, over time, the perpendicular distance from the arc to the shadowing object. The algorithm assumes the shadowing object is a sphere, and adds a safety zone of ten percent to the actual radius to ensure the signal can be routed around the shadowing object before the link breaks.



Given two vertices J and K, to calculate the perpendicular distance, let R_O be the displacement vector of an obstacle with radius r, and let $B_J = R_O$ - R_J represent the position of the obstacle relative to vertex J.

Let

$$V_O = \frac{dR_O}{dt} \tag{15}$$

be the velocity of the obstacle. The perpendicular distance from the arc A_{JK} to the obstacle is

$$D_{JK} = |\hat{A}_{JK} \times B_J| = \frac{|A_{JK} \times B_J|}{|A_{JK}|} \tag{16}$$

Where $\hat{A}$ is the unit vector parallel to A_{JK}. The derivative of the perpendicular distance is

$$\frac{dD_{JK}}{dt} = \frac{d}{dt}\frac{|A_{JK} \times B_J|}{|A_{JK}|} = \frac{d}{dt}\sqrt{\frac{(A_{JK} \times B_J) \cdot (A_{JK} \times B_J)}{A_{JK} \cdot A_{JK}}} \tag{17}$$

This equation becomes

$$\frac{2\frac{|A_{JK} \times B_J|}{|A_{JK}|^2} \cdot \frac{d}{dt}A_{JK} \times B_J - 2\frac{|A_{JK} \times B_J|^2}{|A_{JK}|^3}\frac{d}{dt}L_{JK}}{\frac{2|A_{JK} \times B_J|}{|A_{JK}|}} \tag{18}$$

Note:

$$\frac{d}{dt}A_{JK} \times B_J = \frac{dA_{JK}}{dt} \times B_J + A_{JK} \times \frac{dB_J}{dt} = (V_K - V_J) \times B_J + A_{JK} \times (V_O - V_J) \tag{19}$$

Then, based upon the equation

$$\frac{dL_{JK}}{dt} = \frac{A_{JK}}{|A_{JK}|} \cdot (V_K - V_J) \tag{20}$$

$$\frac{d}{dt}D_{JK} = \frac{A_{JK} \times B_J}{|A_{JK} \times B_J|} \cdot \frac{(V_K - V_J) \times B_J + A_{JK} \times (V_O - V_J)}{|A_{JK}|} - \frac{|A_{JK} \times B_J|}{|A_{JK}|^3} A_{JK} \cdot (V_K - V_J) \tag{21}$$

In this equation, all quantities on the right hand side of the equation can be calculated from the positions and velocities of the vertices and obstacle. Occlusions are a concern only when the closest point of the approach to the obstacle is between the end points of the arc. This happens when both of the following conditions hold:

$$(R_K - R_J) \cdot (R_O - R_J) > 0 \tag{22}$$

$$(R_J - R_K) \cdot (R_O - R_K) > 0 \tag{23}$$

Using a linear approximation

$$r = D_{JK} + \frac{d}{dt} D_{JK} t \tag{24}$$

The time to occlusion by the obstacle's edge can be calculated as follows:

$$t + \frac{r - D_{JK}}{\frac{dD_{JK}}{dt}} \tag{25}$$

Normally, $D_{JK} > r$ and this constraint is only of concern when

$$\frac{d}{dt} D_{JK} < 0 \tag{26}$$

This means the obstacle is getting closer to the line of sight.

The routing algorithm will perform these calculations periodically and an arc will be dropped from the routing tables if the time t from equation 12 or equation 24 is less than two periods. In order to economize on the hardware, we have proposed a configuration in which each node is connected to its nearest neighbors satisfying the constraints implied by the above, up to a maximum of two connections for each node. If the ships are close enough so that both nearest neighbors satisfy the constraints, this connection policy results in a ring that enables all of the nodes to communicate even if one of the links is severed. Since the constraints are re-evaluated periodically, new connections can be formed when weak connections are dropped, and the identity of the two nearest neighbors can change as the ships change their relative positions, with corresponding changes to the routing patterns.

6 Relevant Research

The research surveyed in this section supports, either directly or indirectly, the NPRP concept. As with any software, NPRP architecture, interoperability, quality of service and reliability must be well-planned and optimal. The research abstracts below provide a window into each graduate's unique research along with a brief explanation of the relevance to NPRP.

6.1 Integrating Stand-Alone Systems

Dr. Paul Young's research identified a method for meeting the need for interoperability among independently developed heterogeneous operating systems, host languages and data models. [7]

The approach articluated in the research has applicability to nautical predictive routing protocol for the dynamic ad-hoc naval network. It is expected that the integrated ships' systems required to host and maintain the NPRP software are likely to be from a variety of independent development contracts and would reflect the developer's strengths, the age of the ship and the technology available at that time. The Object Oriented Method for Interoperability provides a potential methodology for enabling operations among the various systems that may be used in the NPRP and DANN architecture.

Abstract. [7] Meeting future system requirements by integrating existing stand-alone systems is attracting renewed interest. Computer communications advances, functional similarities in related systems, and enhanced information description mechanisms suggest that improved capabilities may be possible; but full realization of this potential can only be achieved if stand-alone systems are fully interoperable. Interoperability among independently developed heterogeneous systems is difficult to achieve: systems often have different architectures, different hardware platforms, different operating systems, different host languages and different data models. The Object-Oriented Method for Interoperability (OOMI) introduced in this dissertation resolves modeling differences in a federation of independently developed heterogeneous systems, thus enabling system interoperation. First a model of the information and operations shared among systems, termed a Federation Interoperability Object Model (FIOM), is defined. Construction of the FIOM is done prior to run-time with the assistance of a specialized toolset, the OOMI Integrated Development Environment (OOMI IDE). Then at runtime OOMI translators utilize the FIOM to automatically resolve differences in exchanged information and in inter-system operation signatures.

6.2 Layered Abstraction Approach

Dr. Michael Dabose proposes a component-based layered abstraction approach to software development that creates an environment for porting software from one platform to another. [8] Given the expected disparity in sensors and computing platforms existing among warships of various classes and vintages, the layered abstraction approach can be considered for the implementation phase following successful proof-of-concept exercises and demonstrations.

Abstract. [8] The current state of the art techniques to describe and implement a hard real time embedded software architecture for missile systems range from inadequate to totally nonexistent. Most of the existing software implementations within such systems consist of hand coded functionality, optimized for speed, with little or no thought to long term maintainability, and extensibility. Utilizing current state of the art software development technology, the first ever software architecture for hard real time missile software has been designed and successfully demonstrated. This component based layered abstraction pattern approach to software architecture revolutionizes reduced development time, cost, provides an order of magnitude decrease in error, and is the first such software architecture to function within the hard time constraints of the most extreme cases related to missile systems. Additionally, componentization of functionality allows for porting of software developed for one missile to any other missile with no modification. Hardware obsolescence is overcome by software abstraction layers which isolate the hardware instance from the software functionality providing a rapid, low cost transition of software from one instance of missile hardware to another. The end result of this research is a software architecture demonstrating the capability of managing complex functionality in an accurate, quantifiable, and cost effective manner.

6.3 Quality of Service Execution Path

The quality of service execution path defined by Dr. John Drummond addresses a weakness in wireless QoS by identifying and mitigating QoS conflicts that occur during program execution. [9] Quality of service goals, such as network latency, jitter and dropped packets may not necessarily result from physical network issues. Improving quality of service is one of the motivations for the DANN. It is important to optimize the program execution path to maximize quality of service prior to adding the network itself to the environment.

Abstract. [9] The substantial complexity and strict requirements of distributed command & control systems creates an environment that places extreme demands upon system resources. Furthermore, inconsistent resource distribution also introduces the distinct possibility of potential errors, and process failures. Many of these potential difficulties can be understood and addressed through a practical analysis of the resource management and distribution procedures employed within these systems. This analysis should include a direct focus upon the essential quality of service that is shared among the software programs that operate within this environment. However, the current approaches to this analysis are lacking in that there is no accurate method to determine precisely what quality of service based conflicts take place during program execution. This problem can be addressed through examination of specific quality of service actions during program execution. To achieve a precise analysis of quality of service actions this dissertation research has implemented an approach to examine the exact quality of service execution path during program operation.

6.4 Architecture Readiness Levels

Dr. Kevin Greaney's research proposes a software architecture based approach for simulation model representations.[10] As the current NPRP simulation model grows in complexity, it is important to ensure its interoperability with other network and communication models. The approach described in Dr. Greaney's dissertation provides a baseline for building simulation models with a higher degree of interoperability certainty.

Abstract. [10] National- and Department-level decision-makers expect credible Department of Defense models and simulations (M&S) to provide them confidence in the simulation results, especially for mission-critical and high-risk decisions supporting National Security. Many of these large-scale, software-intensive simulation systems were autonomously developed over time, and subject to varying degrees of funding, maintenance, and life-cycle management practices, resulting in heterogeneous model representations and data. Systemic problems with distributed interoperability of these non-trivial simulations in federations persist, and current techniques, procedures, and tools have not achieved the desired results. The Software Architecture-Based Product Line for simulation model representations, employing Architecture Readiness Levels presented in this dissertation provides an alternative methodology. The proposed four-layered M&S software architecture-based product line model enables the development of model representations supported by readiness levels. Each layer reflects a division of the software architecture-based product line. The layer represents a horizontal slice through the architecture for organizing viewpoints or views at the same level of abstraction while the software architecture-based product line represents a vertical slice. A layer may maintain multiple views and viewpoints of a software architecture-based product line. A Domain Metadata Repository prescribes the interaction between layers. We introduce the Domain Integrated Product Development Team concept.

6.5 Efficiency and Effectiveness Model

Dr. Grant Jacoby's Intranet efficiency and effectiveness model [11] directly supports the NPRP approach in that NPRP is a predictive routing protocol for a wireless intranet servicing a formation of ships at sea. The evaluation of critical business requirements maps directly to the network "human intervention" described earlier in this paper. A process to identify and measure critical business requirements and their associated variables has the potential to increase intranet quality of service within DANN nodes, as well as throughout other intranet applications.

Abstract. [11] This research provides the first theoretical model – the Intranet Efficiency and Effectiveness Model (IEEM) – for the Family of Measures approach to measure Web activity as well as a holistic framework and multi-disciplinary quality paradigm approach not previously derived in viewing and measuring intranet contributions in the context of a corporations overall critical business requirements. This is accomplished by applying a balanced baseline set of metrics and conversion ratios linked to business processes as they relate to knowledge workers, IT

managers and business decision makers seeking to increase value. It also outlines who should conduct these measurements and how in the form of a business intelligence team and provides a means in which to calculate return on intranet metrics investment (ROIMI) with a common unit of analysis for both aggregate and sub-corporate levels through forms of the Knowledge Value Added (KVA) and Activity Based Costing (ABC) methodologies.

6.6 Hoslistic Framework for Software Architecture

Dr. Joseph Puett proposes a software engineering holistic framework that identifies interoperable synergies among software development tools and models.[12] NPRP modeling for the DANN is an essential step towards live testing at sea. The expense associated with live testing must be mitigated by proof-of-concept modeling, and Dr. Puett's research supports enhanced modeling among the various subsystems that will ultimately comprise the DANN. The identification and quantification of synergistic dependencies described in this research provide a potential framework for developing NPRP solutions for multiple topographies.

Abstract. [12] This dissertation presents a Holistic Framework for Software Engineering (HFSE) that establishes collaborative mechanisms by which existing heterogeneous software development tools and models will interoperate. Past research has been conducted with the aim of developing or improving individual aspects of software development; however, this research focuses on establishing a holistic approach over the entire development effort where unrealized synergies and dependencies between all of the tools' artifacts can be visualized and leveraged to produce both improvements in process and product. The HFSE is both a conceptual framework and a software engineering process model (with tool support) where the dependencies between software development artifacts are identified, quantified, tracked, and deployed throughout all artifacts via middleware. Central to the approach is the integration of Quality Function Deployment (QFD) into the Relational Hypergraph (RH) Model of Software Evolution. This integration allows for the dependencies between artifacts to be automatically tracked throughout the hypergraph representation of the development effort, thus assisting the software engineer to isolate subgraphs as needed.

6.7 Software System Safety Index

Dr. Christopher Williamson's research provides a software engineering methodology for identifying software system weaknesses and for preventing potential catastrophic system failures.[13] This correlates directly with NPRP and the DANN in that software system failures in times of armed conflict, although perhaps not catastrophic, may have catastrophic results. Dr. Williamson's approach identifies ways to improve software safety and reliability, both necessary for a system such as that supported by NPRP.

Abstract. [13] The current state of the art techniques of Software Engineering lack a formal method and metric for measuring the safety index of a software system. The lack of such a methodology has resulted in a series of highly publicized and costly catastrophic failures of highassurance software systems. This dissertation introduces a formal method for identifying and evaluating the weaknesses in a software system using a more precise metric, counter to traditional methods of development that have proven unreliable. This metric utilizes both a qualitative and quantitative approach employing principles of statistics and probability to determine the level of safety, likelihood of hazardous events, and the economic costbenefit of correcting the flaws through the lifecycle of a software system. This dissertation establishes benefits in the fields of Software Engineering of highassurance systems, improvements in Software Safety and Software Reliability, and an expansion within the discipline of Software Economics and Management.

6.8 Mass-Spring Application to Network Connectivity

Dr. William Roof's research into predictive signal routing and communication graph node positioning inserts mass-spring theory NPRP into the system to maintain node connectivity.[14] This approach decentralizes the network control by identifying a methodology by which each node operates as an independent agent. The distributed approach improves the robustness of the system, relieves network traffic and enhances network quality of service.

Abstract. [14] The truly unique contribution within NPRP is the application of Mass-Spring theory to maintain connectivity between the vertices in the DANN. This is the first ever application of this methodology to mobile ad-hoc wireless networks at sea. The approach, algorithms, and object classes developed to model the approach constitute new contributions as well. The goal of this research is to leave the WiFi standards in place, and to handle key network issues such as load balancing and quality of service by identifying system constraints and by developing software routing that predicts network connection problems and adjusts the topology prior to the problems occurring. The identification of the topology and the hardware constraints that keep the system extremely simple provide a means to model and test low-cost, commercial 802.11x equipment without extensive software engineering rework of the existing protocol stack.

7 Conclusions

The Dynamic Ad-Hoc Nautical Network presents unique challenges to signal routing over a wireless network. The ability to employ a protocol that is predictive, that encompasses the best attributes of both static and dynamic protocols, and that can calculate course and speed to position vertices properly before they lose connectivity, should increase network QOS beyond that available through standard wireless routing protocols.

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